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Phase-change materials for indoor comfort improvement in lightweight buildings. A parametric analysis for Australian climates

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Abstract

Phase change materials (PCM), being able to supply dynamic thermal capacity, have ever shown great potentialities in lightweight constructions. Following a first study on the integration of PCM in lightweight solar walls, this paper aims to explore the integration of PCMs in walls and partitions, carrying out a multi-parametric study.
A test room, representing a naturally conditioned typical office, has been simulated in EnergyPlus. PCM have been modelled as integrated either in indoor partitions or in external walls. The variation of parameters such as the position of the PCM layer within the component (outer or inner position), the thickness of PCM's layer and PCM's transition range have been considered.
Comfort indicators, such as the frequency of thermal discomfort, have been calculated defining the most beneficial integration strategy.

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Keywords: Phase-Change Materials, lightweight construction, Australian Climate, Building Envelope

Nomenclature

U	Thermal transmittance of the construction element [$W \cdot m^{-2} \cdot K^{-1}$]
W	Own weight of construction element [$kg \cdot m^{-2}$]
TnC	Time non comfortable according to ASHRAE 55-2010 adaptive thermal comfort model [h]
T_S	Average seasonal indoor surface temperature [°C]

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1. Introduction

Building industry is moving toward more and more lightweight technologies with sensible improvements in manufacturing processes and in environmental benefits, due to the simultaneous reduction of component's weight and embodied grey energy.

However, reduction of heat storage of building fabric tends to decrease the stability of radiant temperature of indoor surfaces, especially under outdoor conditions with high temperature and solar irradiance gradients. This will significantly decrease the comfort sensation perceived by the users.

Phase change materials (PCM) have ever shown great potentialities in the supply of dynamic thermal capacity of lightweight constructions, and more and more scientific studies are concentrating their attention to such as these smart materials [1]. The benefits of integrating PCM in buildings are not only due to the stabilization of thermal flux through building components, but also to the shifting of HVAC systems' peak loads [2]. Integration strategies of PCM in lightweight construction for increasing winter and summer energy storage has been recently evaluated under different climatic conditions [3], pointing out that the determination of the optimal PCM phase transition range should be based on climate. Furthermore position and thickness of PCM layers within the external envelope are other determinant parameters.

However, as pointed out in several researches [1] a more systematic evaluation of building integration of PCM materials, performed using clear indicators, is needed. Several studies have already defined the benefits of different integration strategies. Zwanzig et al. [3] have defined an optimal location for PCM inclusion in external envelope's building components based on exterior boundary conditions. Kuznik et al. [4] have optimized PCM's thickness focusing on the indoor/outdoor temperature gradient over a control period of 24 hours. A research carried out by Pouland & Fung [5] has defined the relationship between thermal conductivity, PCM's melting point range and indoor temperature fluctuations in Net Zero Energy houses in cold climates. Furthermore several studies performed by Evola et al. [6] and Kendrick & Walliman [7] have depicted the relationships between thermal comfort and parameters such as thickness and melting point range of PCM's layers, but concentrating only on the summer season.

Following a first study on the integration of PCMs in lightweight solar walls [8], this paper aims to explore the potentialities of integrating PCMs in walls and partitions of office buildings carrying out a multi-parametric study. As outlined before, previous researches have only been concentrated on the relationship between one single parameter and indoor comfort indicators or have carried on multi-parametric analyses during one single season. The final aim is to relate, for the first time, all the main parameters affecting PCM's performance (building component, position within the building component, thickness of phase change layer, melting point range) with indoor comfort indicators, carrying out a yearly analysis. In order to increase the significance of the research, it has been modelled a building placed in a temperate climate zone with hot summers (represented by the Australian climatic zone 5), requiring both summer and winter optimization of design parameters.

2. Methodology

A test room, similar in geometry and materials to the one modelled in [8] has been modelled with DesignBuilder and simulated through the EnergyPlus™ [9]. The test room has an internal area of 25 m^2 (square footprint, 5 m of side) and is representative of a typical office room shared by two users.

The room has been modelled with an external wall exposed to south in order to avoid any penetration of direct solar radiation. The external exposed wall is partially transparent, with a window to wall ratio of 0.3. All the other surfaces have been modelled as adiabatic, thus simulating an internal office in an intermediate floor. In the following Table 1 a detail of the properties of the modelled construction elements is included. In order to evaluate the benefits associated with the inclusion of PCMs in building components, lightweight (own weight less than 200 kg/m^2) and well insulated (thermal transmittance lower than 0.4 W/m^2K) envelope solutions have been considered.

The following parameters have been included in the evaluation:

- Building component in which the PCM is integrated (south and north walls, indoor partitions)
- Position of the PCM layer within the component (outer or inner layer)
- Thickness of the PCM layer within the components
- PCM phase transition range

The modelled test room is representative of a typical office (class 5 building according to the Australian National Construction Code [10]). Internal gains, as well as ventilation losses/gains have been considered accordingly with the supposed use. In detail:

- Internal gains due to users' occupancy: 2 people undertaking normal activities (75 W/p of sensible heat gain and 55 W/p of latent heat gain) during office hours. The occupancy schedule has been set up accordingly to [10].
- Internal gains due to artificial lighting: 9 W/m^2. Artificial lighting has been simulated dimmable, in order to achieve, in combination with natural lighting, an illuminance of at least 500 lux at the reference point (placed at 75 cm of height from the floor in the middle of the room) during occupied hours.
- Internal gains due to appliances: 15 W/m^2 with an operational schedule defined according to [10].
- Ventilation rate: 1 ach due to air infiltration and up to 2 ach of direct natural ventilation. Direct natural ventilation is activated when the indoor air temperature exceeds the threshold of 26°C and contemporary the outside air temperature is lower than the indoor one.

In order to assess the benefits of PCM inclusion in construction elements, the test room has been modelled as completely naturally conditioned. Thus HVAC system and mechanical ventilation has not been modelled. Moreover, the parametric analysis has been based on indoor thermal comfort variables.

Table 1: properties of the construction elements

Construction element	Layers (outside to inside)	U	W
External wall (PCM outside)	Cement Plasterboard (25 mm) PCM layer (0-40 mm) Mineralized wood (40-0 mm) Polystyrene (80 mm) Gypsum Plasterboard (25 mm)	0.33	105
External wall (PCM inside)	Cement Plasterboard (25 mm) Polystyrene (80 mm) Mineralized wood (0-40 mm) PCM layer (0-40mm) Gypsum Plasterboard (25 mm)	0.33	105
Partitions	Gypsum plasterboard (25 mm) PCM layer (0-80 mm) Mineralized wood (80-0 mm) Gypsum plasterboard (25 mm)	adiabatic layer	125
Floor	Reinforced concrete slab (250 mm) Air gap (250 mm) Timber flooring (30 mm)	adiabatic layer	15 (exposed thermal mass)
Ceiling	Reinforced concrete slab (250 mm) Air gap (250 mm) Gypsum plasterboard (13 mm)	adiabatic layer	15 (exposed thermal mass)

3. Theory and calculation

The reliability of EnergyPlus^{TM} as a tool capable of predicting the thermal behaviour of lightweight constructions has been widely demonstrated, validating the results of simulations with in-site measurements [11]. Furthermore, the consistency of EnergyPlus in modelling basic PCMs and PCMs integrated in building components has been tested in several research projects [6], [12].

In this work the "*conduction finite difference* (CondFD)" algorithm has been used and the "*fully implicit first order specific scheme"* has been adopted [13]. The choice of this method is necessary when dealing with PCMs, as their specific heat capacity at each time step (depending on the specific enthalpy) is a function of temperature. The curve enthalpy-temperature can be provided by the user and is a specific characteristic of each material.

In the current work, 4 different PCMs have been simulated. All are based on n-Paraffins and Waxes.

- RT21, with a melting range between 18°C and 23°C and a total heat storage capacity (combination of latent and sensible heat) in the temperature range 13°C-28°C of 160 kJ/kg.
- RT27, with a melting range between 25°C and 28°C and a total heat storage capacity in the temperature range 20°C-35°C of 179 kJ/kg.
- RT31, with a melting range between 27°C and 33°C and a total heat storage capacity in the temperature range of 23°C-28°C of 170 kJ/kg.
- RT42, with a melting range between 38°C and 43°C and a total heat storage capacity in the temperature range 35°C-50°C of 174 kJ/kg.

The CondFd algorithm allows also to set a different simulation grid discretization as a function of the thermal diffusivity of the material (α) and of the time step (Δt), by providing a space discretization constant C. In this work, a time step Δt of 120 s and a space discretization constant C of 3 have been set up, in order to obtain a simulation grid comparable with the thickness of each construction layer.

As output, two main comfort indicators have been chosen:

- Time non Comfortable (TnC, measured in hours): number of hours in which the indoor operative temperature T_O is outside the range of acceptability for naturally conditioned spaces. The range has been chosen according to the adaptive model described in [14] for a 90% acceptability. The adaptive model accounts also for local discomfort effects in typical buildings and for people's clothing adaptation, as it relates the acceptability range to outdoor climate.
- T_S : average seasonal indoor surface temperature of the partitions or walls considered.

All the simulations have been performed for the Australian climatic area 5 according to [10], considering Sydney (33°52'59'' S, 151°13'0'' E) as the reference city. A typical statistical year has been considered and the results have been obtained for the entire year, for the summer design week (6-12 January) and for the winter design week (17-23 August).

4. Results and discussion

4.1. Variation of indoor temperatures

In Figure 1, the seasonal surface temperature of the partition is represented as a function of PCM layer thickness and of PCM melting point range. The seasonal surface temperature has been calculated as the average surface temperature during the design week. Both in winter – Figure 1a) – and in summer – Figure 1b) – the inclusion of PCM in partitions is able to stabilize surface temperatures within a range of acceptance. Closer is the average surface temperature (and thus the average temperature of PCM layer) to the melting range, higher is the temperature decrease. Interestingly the reductions are not depending linearly on the PCM layer's thickness, with a levelling of the curves for thicknesses higher than 6 cm.

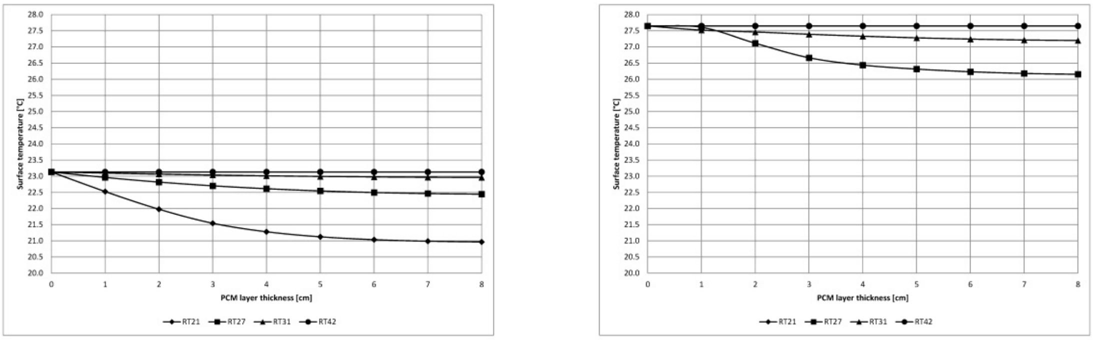

Figure 1: Average seasonal partition's surface temperature T_S: a) winter, b) summer

A similar behaviour can be found analysing PCM's integration in external walls for both summer and winter seasons (Figure 2 and Figure 3). The integration of PCM in wall's innermost layer (the one directly exposed to indoor environment) helps in stabilizing surface temperatures (Figure 2a and Figure 3a).

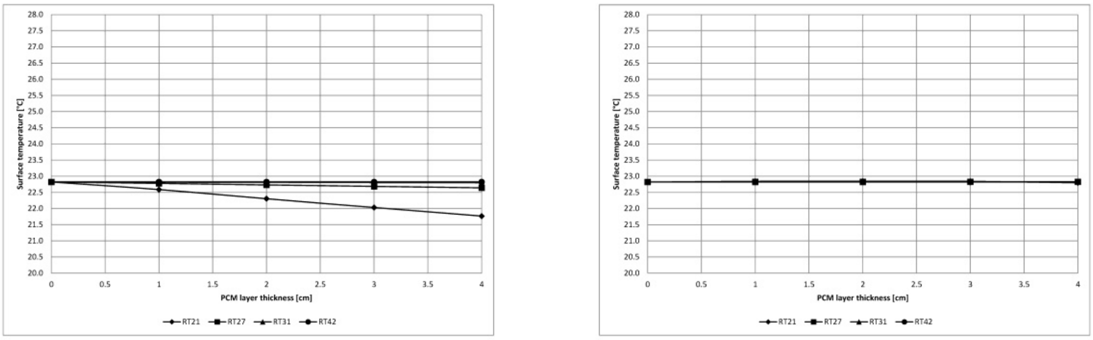

Figure 2: Average seasonal wall's surface temperature T_S during winter: a) PCM integrated in the innermost layer, b) PCM integrated in the outermost layer.

Contrarily, due to the presence of the intermediate thermal insulation layer, the integration of PCMs in the outermost wall's layer has no effect on the variation of winter (Figure 2b) and summer (Figure 3b) seasonal average surface temperature.

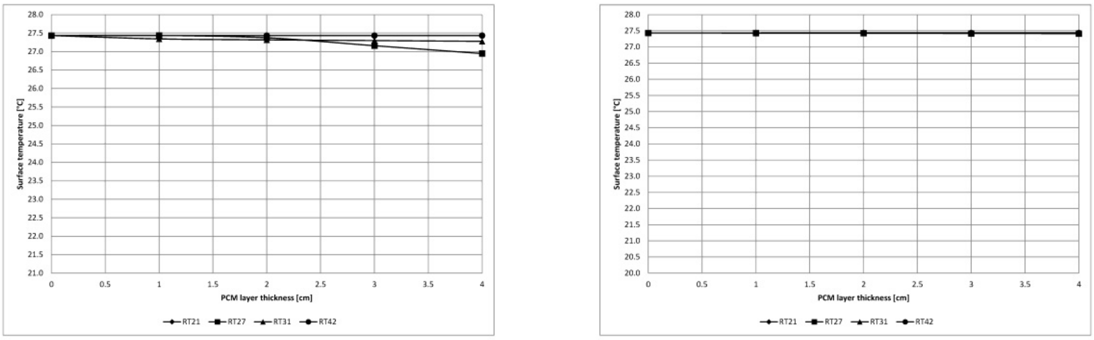

Figure 3: Average seasonal wall's surface temperature T_S during summer: a) PCM integrated in the innermost layer, b) PCM integrated in the outermost layer.

4.2. Variation of comfort levels

The data described in the previous paragraph can help in analysing the assessment of winter, summer and annual comfort conditions. A reduction of the number of discomfort hours can be found during both summer and winter with the adoption of PCMs in partitions. During the typical winter week (Figure 4a) the discomfort can be reduced of up the 95% using RT27 or RT31, even with very thin layers. Also in summer (Figure 4b) the adoption of both RT27 and RT31 can generate benefits to indoor comfort conditions, with a reduction of the number of discomfort hours of up the 55%.

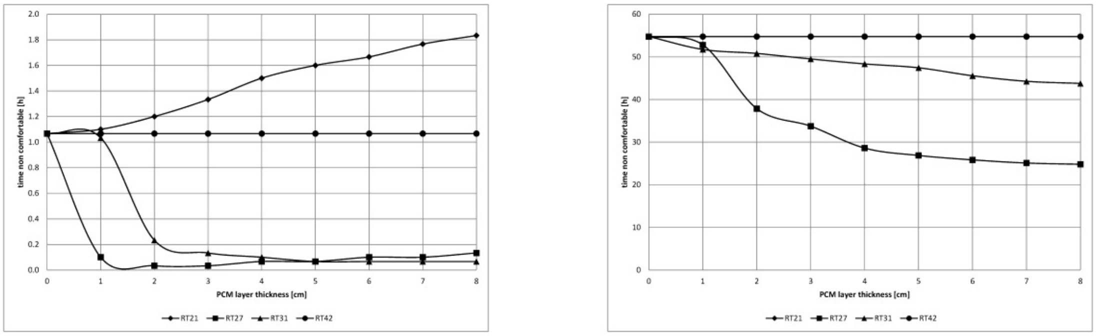

Figure 4: TnC for PCM integrated in indoor partitions: a) winter's design week, b) summer's design week

Overall, during a typical year (Figure 5), the RT27 has been discovered as the best performing material, with reductions of up to 160 hours of discomfort (equivalent to more than the 10% of the yearly discomfort hours). As thermal comfort depends on the mean radiant temperature, the pattern of TnC is directly linked with the pattern of T_S. In detail, it can be noticed also a flattening of the curve TnC/ PCM's thickness for thicknesses higher than 6 cm.

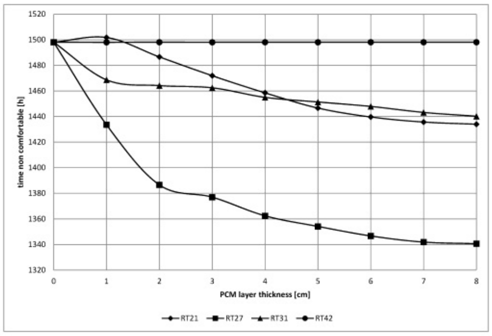

Figure 5: TnC for PCM integrated in indoor partitions during a typical year

Moreover, the integration of PCM in outside walls is beneficial for the indoor comfort conditions. During the winter typical design week (Figure 6), up to a 60% of reduction of the total number of non comfortable hours can be achieved integrating RT27 in the innermost layer.

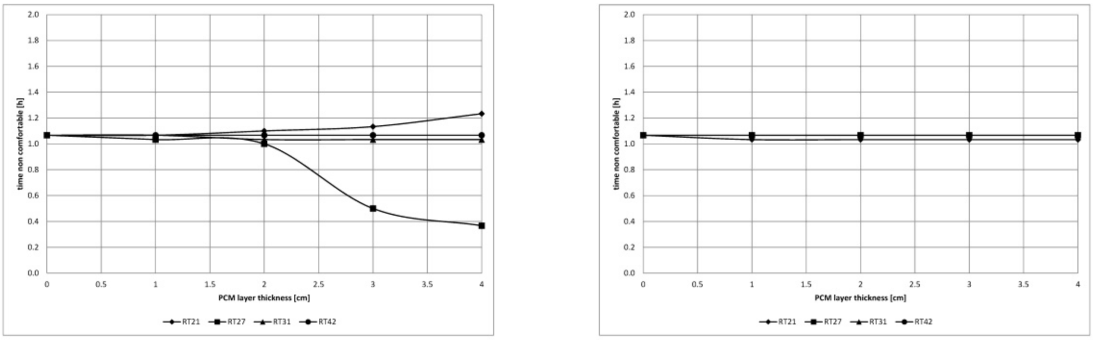

Figure 6: TnC during the winter design week: a) PCM integrated in wall's innermost layer, b) PCM integrated in wall's outermost layer

A similar result, even if with lower benefits (up to the 10% of reduction of discomfort hours) occurs during summer period (Figure 7).

Overall, during the typical year, an increase of up to 40 comfortable hours can be achieved integrating PCMs in innermost wall's layer. The base high levels of insulation and the reduced area of exposed surface, let the integration of PCM in outermost wall's layer be not significant.

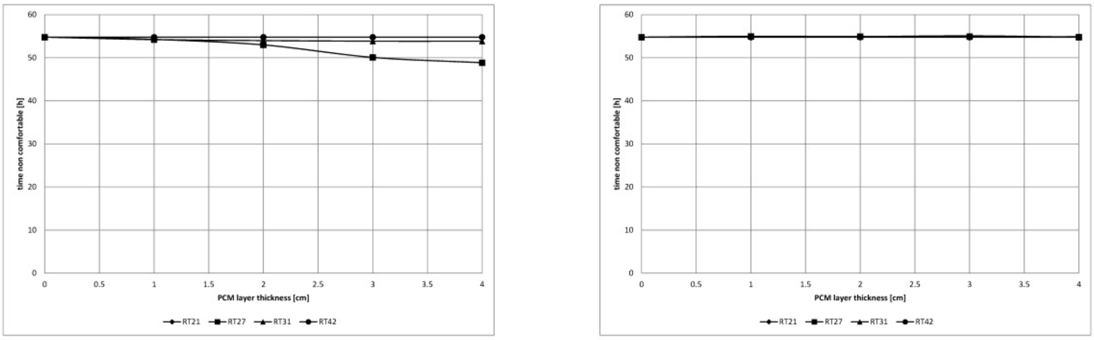

Figure 7: TnC during summer's design week: a) PCM integrated in wall's innermost layer, b) PCM integrated in wall's outermost layer.

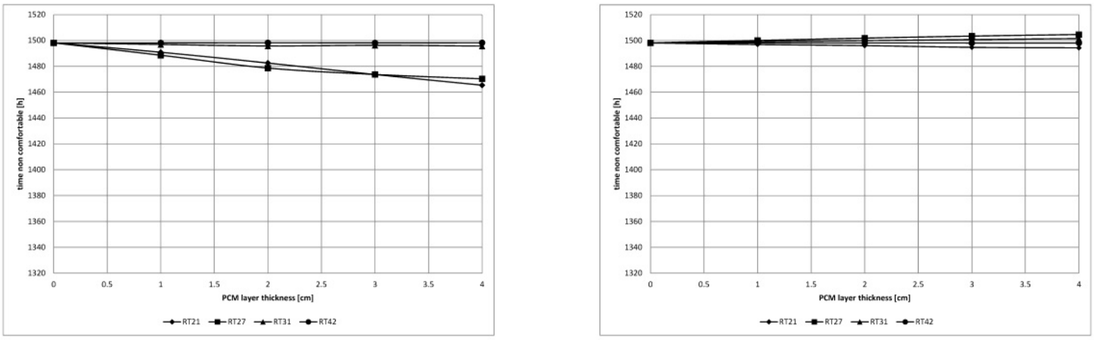

Figure 8: TnC during the typical year: a) PCM integrated in wall's innermost layer, b) PCM integrated in wall's outermost layer

5. Conclusions

As already highlighted by previous researches, PCMs' integration in lightweight building components is highly beneficial, as it is able to minimize the fluctuation of radiant temperatures. Previous studies demonstrated the benefits of PCMs integration in lightweight buildings, also comparing different climatic zones, but a multi-parametric analysis was needed.

In the paper, a simple test room, representative of a typical office has been modelled. The natural conditioned space has been equipped with PCMs integrated in indoor partitions and in external walls. 4 typical materials have been analysed, with melting point ranges varying between 18°C and 43°C.

The number of discomfort hours, calculated with the adaptive model included in ASHRAE 55 code, has been used as main parameter for the assessment of most beneficial strategy of integration.

From the results of simulations, it has been noticed that:

- The highest benefit can be obtained by the integration of PCMs in inner surfaces (either partition or walls). The material is, thus, able to stabilize more effectively indoor radiant temperature, reducing local and global thermal discomfort.

- In very well insulated buildings, the thermal barrier constituted by the thermal insulation, makes the phase change material be not effective if integrated in innermost layers.
- The benefits are directly depending on the thickness of PCM layer and on the area of exposed surface (integration in partition more effective than in external walls). However the linear dependence between decrease of discomfort hours and increase of PCM's thickness is valid only for limited thicknesses (lower than 6 cm).
- In the case of free-running buildings, the melting point range of the phase change material should be chosen in order to match with the average maximum outdoor temperatures of the climatic zone considered. For example, in Sydney, the best performing material is the RT27, with a melting point range between 25°C and 28°C.

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